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TRANSITION FROM POPULATION III TO POPULATION II STARS

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ABSTRACT

The transition from Population III to Population II stars is determined by the presence of a sufficient amount of metals, in particular, oxygen and carbon. The vastly different yields of these relevant metals between different initial stellar mass functions would then cause such a transition to occur at different times. We show that the transition from Pop III to Pop II stars is likely to occur before the universe can be reionized, if the IMF is entirely very massive stars ($M \geq 140\,M_{\odot}$). A factor of about 10 more ionizing photons would be produced in the case with normal top-heavy IMF (e.g., $M \sim 10-100\,M_{\odot}$), when such a transition occurs. Thus, a high Thomson optical depth ($\tau_e \geq 0.11-0.14$) may be indication that the Population III stars possess a more conventional top-heavy IMF.

Subject headings: stars: abundances — supernovae: general — galaxies: formation — intergalactic medium — cosmology: theory — early universe

1. INTRODUCTION

Recent observations of the high redshift ($z > 6$) quasar spectra from the Sloan Digital Sky Survey (SDSS) and the cosmic microwave background fluctuations from the Wilkinson Microwave Anisotropy Probe (*WMAP*) combine to paint a complicated reionization picture (Fan et al. 2001; Kogut et al. 2003). While it seems relatively secure to claim that the reionization process has begun at $z \geq 10$ and ends at $z \sim 6$ (e.g., Fan et al. 2001; Becker et al. 2001; Barkana 2002; Cen & McDonald 2002), exactly when it starts and how it evolves are yet unclear, although the overall picture is consistent with a physically motivated double reionization model (Cen 2003; Wyithe & Loeb 2003) that was proposed before WMAP released its reionization measurement. The conventional wisdom is that stars are primarily responsible for producing most of the ionizing photons. Unavoidably, there is a transition epoch from metal-free Population III (Pop III) to metal-poor Population II (Pop II) stars at some high redshift (see, e.g., Omukai 2000; Bromm, Ferrara, Coppi, & Larson 2001; Schneider, Ferrara, Natarajan, & Omukai 2002; Mackey, Bromm, & Hernquist 2003; Schneider et al. 2003; Bromm & Loeb 2003).

It is thought that Pop III stars may be much more massive than Pop II stars. This expectation is based on the physics of metal cooling. Lack of metals in the gas at early times results in an absolute floor temperature of gas at $\sim$ 100K, whereas a small but significant amount of metals would enable gas to cool down to $\sim$ 10K. Consequently, Pop III stars are expected to be much more massive than Pop II stars (Carr, Bond, & Arnett 1984; Larson 1998; Abel, Bryan, & Norman 2000; Hernandez & Ferrara 2001; Bromm, Ferrara, Coppi, & Larson 2001; Bromm, Kudritzki, & Loeb 2001; Nakamura & Umemura 2001; Bromm, Coppi, & Larson 2002; Omukai & Palla 2003; Mackey, Bromm, & Hernquist 2003). However, how massive Pop III stars are remains unclear. While simulations have suggested that Pop III stars may be more massive than $100\,M_{\odot}$ (“vary massive star”, VMS; Abel, Bryan, & Norman 2000; Bromm, Ferrara, Coppi, & Larson 2001), Tan & McKee (2004) argue that taking into account feedback processes would likely limit the mass of the Pop III stars to the range $30-100\,M_{\odot}$. Observationally, the VMS picture is advocated by Oh, Nollett, Madau, & Wasserburg (2001) and Qian & Wasserburg (2002), based on the argument that the metal yield patterns from pair-instability supernova (PISN) explosion of VMS progenitors (Heger & Woosley 2002) are consistent with observations (see also Wasserburg & Qian 2000; 2001). On the other hand, Tumlinson, Venkatesan,& Shull (2004) argue that the general pattern in metal-poor halo stars, especially the Fe-peak and r-process elements, favors the yield pattern of Type II supernovae (SNII) with an initial mass function (IMF) above 10 $M_{\odot}$ and without VMS (see also Daigne et al. 2004). Other arguments based on observations such as metallicities of the intergalactic (IGM) at $z \sim 3-4$ in the Lyα forest (Venkatesan & Truran 2003) and cosmic star formation history (Daigne et al. 2004) also favor a SNII type IMF. Umeda & Nomoto (2003) and Umeda & Nomoto (2003) argue that the observed metal abundance pattern are better matched by core-collapsed supernova with $M_{\star} = 10-50\,M_{\odot}$ through pair-instability supernova explosion (Heger & Woosley 2002).

It thus seems beneficial to explore possible differences between different IMFs. In this *Letter*, we investigate the issue of the transition from Pop III to Pop II. Specifically, following Bromm & Loeb (2003), we note that the transition from Pop III to Pop II is dictated by efficiency of cooling by a limited number of species, in particular, C and O. Thus, it is the amount of C and O, not necessarily the total amount of “metals”, that determines the transition. While the ionizing photon production efficiency turns out to be quite comparable in both cases, either with a VMS IMF or a more normal top-heavy IMF (e.g., Tumlinson, Venkatesan,& Shull 2004),

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they have very different metal patterns in the exploded final products. In PISN case the supernova ejecta is enriched by α-elements, whereas the major products of SNII are hydrogen and helium with a small amount of heavy elements (see, e.g., Woosley & Weaver 1995; Heger & Woosley 2002). Consequently, the transition from Pop III to Pop II stars should occur at different times. We show that a normal top-heavy IMF is preferred to VMS and probably required if Pop III stars were to reionize the universe at high enough redshift.

2. TRANSITION FROM POP III TO POP II

We first define $f_\star$ as the baryon fraction that has been processed through Pop III stars, $f_\star \equiv M_{III}/M_b$, where M_b and M_{III} are total baryonic mass and the baryonic mass in Pop III stars, respectively. We also define the total ionization photons ($h\nu \geq 13.6$eV) produced per unit mass of Pop III stars as $< N_{ph} >$ photons $\mathrm{M}_\odot^{-1}$. For completeness we show in Figure 1 the time-integrated ionization photons per solar mass emitted during the lifetime of a Pop III star vs. its initial mass $M_\star$, adopted from Schaerer (2002). The vertical dotted line at $M_\star = 140\,M_\odot$ is to distinguish between PISN and SNII. Clearly, for most of the mass range ($80 \lesssim M_\star < 260\,M_\odot$), the ionizing photons produced during the lifetime of the star is $\sim 10^{62}$ photons $\mathrm{M}_\odot^{-1}$. This lifetime-integrated number of ionizing photons varies only about a factor of less than 2 when the initial mass is $\sim 20\,M_\odot$. It is because the total ionizing photon production of a short-lifetime VMS is boosted by its higher production rate. However, we should keep in mind that photon production rate could be important if the typical recombination time scale is shorter than the lifetime of Pop III stars. The typical lifetimes of a 200 and 25 $M_\odot$ Pop III stars are $\sim 2.2\times10^6$ and 6.5×10^6 yrs (Schaerer 2002). The recombination time scale is roughly $t_{rec} \sim 10^7 (C_{HII}/10)^{-1}$ yrs at redshift $z \sim 17$, where C_{HII} is the clumping factor of H II regions (Ricotti & Ostriker 2004). While in general t_{rec} is longer than the lifetime of Pop III stars, at some overdense regions when $C_{HII} > 20$ the lifetime of a small mass star could be longer than t_{rec}, and in this case more than 1 ionizing photon are necessary to ionize the entire IGM. Having this caution in mind, in the following we assume that all the Pop III stars produce about the same amount of ionizing photons in their lifetime and roughly 1 ionizing photon per atom is needed to reionize the universe. Using relevant numbers and assuming a mean atom weight of $\mu = 0.76$, we find that the number of the ionizing photons per hydrogen atom produced, denoted as N_{ion}, is

$$N_{ion} = 11 \left(\frac{\mu}{0.76}\right)^{-1} \left(\frac{f_\star}{10^{-4}}\right) \left(\frac{< N_{ph} >}{10^{62}\,\mathrm{photons}\,\mathrm{M}_\odot^{-1}}\right). \tag{1}$$

Let us define y_i as the yield of element i, $y_i \equiv M_i/M_\star$, where M_i is the mass of element i produced by the initial stellar mass $M_\star$. Assuming metals produced by supernova explosion can be effectively transported out of the host halos and uniformly pollute the intergalactic medium (IGM), then the IGM metallicity of element i, $Z^i_{IGM} = f_\star y_i$, where $f_\star$ is the baryon fraction defined above. Substituting $f_\star$ from Eq. 1, we can then relate the ionization photon per H atom, N_{ion}, to the IGM metallicity of element i, Z^i_{IGM}:

$$Z^i_{IGM} = \frac{\mu y_i}{< N_{ph} > m_H} N_{ion}. \tag{2}$$

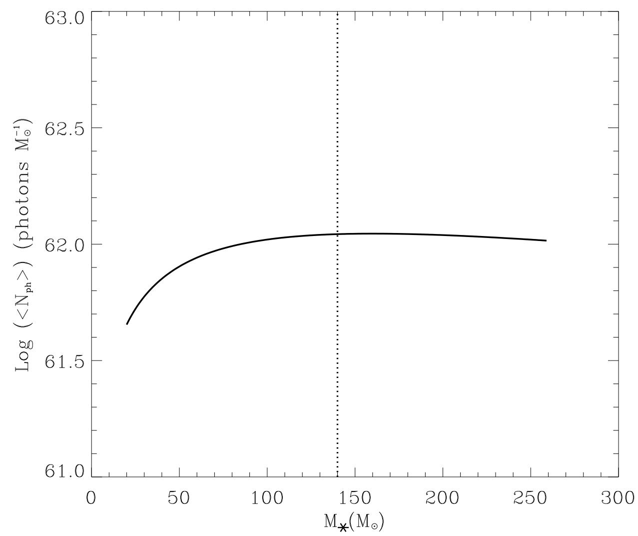

Fig. 1.— Ionization photons produced during the lifetime of a zero-metallicity Pop III star as a function of its initial mass $M_\star$, adopted from Schaerer (2002). The dotted vertical line indicates $M_\star = 140\,M_\odot$. Evidently, the produced ionization photons is nearly a constant for both PISN and SNII cases.

Zero-metallicity Pop III stars with different initial masses have distinctive pattern of final metal productions (see, e.g., Heger & Woosley 2002). For stars with initial masses $10 \lesssim M_\star \lesssim 40\,M_\odot$, neutron stars are formed through type II supernova explosion. The majority of the ejecta are hydrogen and helium, with small amount of heavy metals. Between $40 \lesssim M_\star \lesssim 100\,M_\odot$, black holes form through direct collapse of the star. At $M_\star \sim 100\,M_\odot$, the electron-positron pair instability starts to dominate, but if $M_\star \lesssim 140\,M_\odot$, an iron core will still be formed and eventually collapse to a black hole without any metal productions. When $140 \lesssim M_\star \lesssim 260\,M_\odot$, the pulsation induced by the pair instability is so violent that one single pulse disrupts the entire star and eject abundant α-elements. At above $260\,M_\odot$ again black holes will form. An upper limit of $500\,M_\odot$ of a Pop III star that can be formed from accretion into primordial protostar was recently found by Bromm & Loeb (2004) via three-dimensional numerical simulation. It is important to note that essentially all metals are produced for mass ranges of $10 - 40\ M_\odot$ and/or $140 - 260\ M_\odot$. Pop III stars within these two mass ranges produce distinctive pattern of metals, which will have great impact on the important metal cooling agents, namely, C and O.

We study four types of IMFs: two types for PISN and two types for Type II SN. An IMF is defined as $\Psi(M) \equiv \Psi_0 M^{-\Gamma}$ with Ψ_0

$$\int_{m_1}^{m_2} \Psi_0 M^{-\Gamma} dM = 1. \tag{3}$$

The four types are: (1) PISN model 1, with $140 \lesssim M_\star \lesssim 260\,M_\odot$; (2) PISN model 2, $100 \lesssim M_\star \lesssim 260\,M_\odot$; (3)

Type II Supernova model 1, with $10 \lesssim M_\star \lesssim 140\,M_\odot$; and (4) Type II Supernova model 2, with $30 \lesssim M_\star \lesssim 140\,M_\odot$. Model (2) is introduced to see how sensitive the metal yield of PISN model depends on various mass limits. Model (4) is motivated by the suggestion of Tan & McKee (2004) that the first stars should have masses between $30-100\,M_\odot$. To avoid the degeneracy between the IMF index and mass limits we adopted a consistent IMF index of $\Gamma = 1.5$ among all the four models.

For each IMF we compute the metal yield. As pointed out by Bromm & Loeb (2003) metal cooling at low temperature ($T \le 100$K) is dominated by fine-structure line cooling of C II and O I, we concentrate on the metal yield of C and O. The yield can be calculated through

$$y_i = \int_{m_1}^{m_2} \Psi(M) Y_i(M) dM, \tag{4}$$

where the subscript i represents C or O, and $Y_i(M)$ is defined as the ratio of the mass fraction of the element i in solar units, in this way $Y_i(M)$ is one half of the production factors defined in Heger & Woosley (2002). For the PISN type IMF we use the production factors of Heger & Woosley (2002). For SNII type IMF model 1 and 2 we adopt the production factors calculated from Woosley & Weaver (1995) model Z12A, Z15A, ... and Z30B, Z35B, ... series, respectively.

With metal yield y_i and ionizing photon production rate $< N_{ph} >$, we can now compute the element metallicity Z^i_{IGM} as a function of ionizing photons per hydrogen atom through Eq. 2. The results are shown in Figure 2. The top and bottom panels show the oxygen and carbon metallicities, respectively. The metal abundance in this definition is relative to the solar value, i.e., $[\mathrm{O/H}] = \log_{10}(\mathrm{n_O/n_H}) - \log_{10}(\mathrm{n_O/n_H})_\odot$. The solid and dotted lines represent PISN model 1 and 2, dashed and dot-dashed lines are for SNII model 1 and 2, respectively. The horizontal shadowed areas show the critical transition metallicities Z_{crit} and their errors from Bromm & Loeb (2003), $[\mathrm{C/H}]_{\mathrm{crit}} \simeq -3.5 \pm 0.1$ and $[\mathrm{O/H}]_{\mathrm{crit}} \simeq -3.05 \pm 0.2$, respectively. The free-fall time scale for gas clump is $t_{ff} \approx 5 \times 10^5 (n_H/10^4\,\mathrm{cm}^{-3})^{-1/2}$ yrs, and the critical transition metallicities are obtained by equating the cooling time at temperature $T = 100$K (below which metal cooling dominates) to t_{ff} for a gas density of $n_H = 10^4\mathrm{cm}^{-3}$ (Abel, Bryan, & Norman 2000; Bromm, Coppi, & Larson 2002).

Immediately, we see that the transition from Pop III to Pop II occurs much earlier in Model 1 and 2 than in Models 3 and 4. We see that about $1.0-3.1$ ionizing photons per H atom are produced in PISN Model 1, $3-6$ photons in PISN model 2, whereas $8.6-14$ ionizing photons per H atom is produced in SN II Model 1 and 2. Not all ionizing photons can escape into the IGM, nor do the metals. Metal enrichment of the IGM may be expected to be inhomogeneous, which perhaps would yield a higher effective metal enrichment in star formation regions if galaxy formation is biased. The fact supernova explosions in the PISN (Model 1) may be more energetic than in the other two models may suggest that perhaps more metals could be transported to the IGM in the former case. It thus seems improbable that PISN

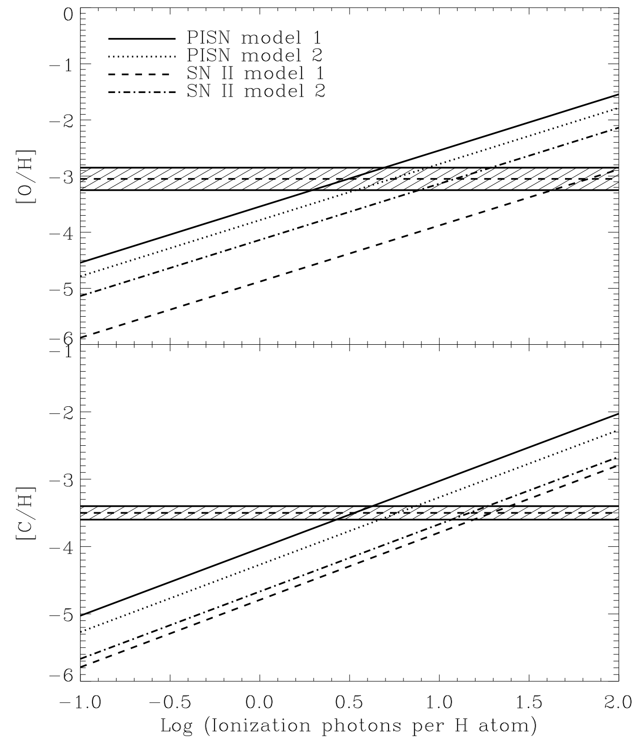

Fig. 2.— Oxygen (top panel) and Carbon (bottom panel) metallicities as a function of the ionizing photons per H atom. The solid and dotted lines represent PISN model 1 and 2, dashed and dot-dashed lines are for SNII model 1 and 2, respectively. The horizontal shadowed areas show the critical transition metallicities and their errors from Bromm & Loeb (2003).

Pop III stars will be able to ionize the universe alone, unless ionizing photon escape fraction is $\ge 20\%$ and/or metal enrichment is very inefficient.

3. CONCLUSIONS

Based on the consideration of cooling due to C and O at low temperatures ($T < 100$K), we note that it may be expected that the transition from Pop III to Pop II stars should occur when ~ 1 ionizing photon per H atom is produced, if the IMF is entirely VMS. A factor of about 10 more ionizing photons would be produced in the case with normal top-heavy IMF (e.g., $M \sim 10-100\,M_\odot$), when such a transition occurs. Thus, it will be much more difficult, if not impossible, to achieve an earlier ($z \gg 10$) reionization in the former case. Therefore, if future WMAP data firm up the Thomson optical depth to $\tau \ge 0.11-0.14$, one may be forced to adopt a more conventional top-heavy IMF. If minihalos were largely responsible for producing ionizing photons at high redshift, then an IMF with VMS may be still viable, as the ionizing photon escape fraction from minihalos may well exceed 50%, shown by the recent radiation hydrodynamic simulations (Whalen, Abel, & Norman 2004; Kitayama, Yoshida, Susa, & Umemura 2004).

We assume that metals can efficiently get mixed

with the general IGM and adopted a simplified picture that metals produced by Pop III stars are uniformly distributed in the IGM. In the PISN case Bromm, Yoshida, & Hernquist (2003) found for a supernova explosion with an energy of $\sim 10^{53}$ ergs, at least 90% of metals can be effectively transported into surrounding IGM. Yoshida, Bromm, & Hernquist (2004) discussed a simplified VMS IMF (all Pop III stars have mass of 200 $M_\odot$ and explode as PISN): they trace the star formation history and calculate the mean number of ionization photons per atom and the mean metalicity of the IGM. Their results are consistent with results from our PISN model 1 and 2. The derived τ_e falls short of *WMAP* result when constrained by a critical metalicity of $[Z/H] = -3.3$, this is consistent with our conclusion that a VMS IMF may not be favored by recent *WMAP* result. However, metal mixing is most likely inhomogeneous, that could affect the transition from Pop III to Pop II stars (see, e.g., Scannapieco, Schneider, & Ferrara 2003; Mackey, Bromm, & Hernquist 2003; Yoshida, Bromm, & Hernquist 2004). The exact effect is, however, unclear, when coupled with spatially non-uniform galaxy and star formation.

We emphasize that a conventional IMF may not be the only way to alleviate the conflict between the metal yield of the Pop III stars and the number of ionization photons they produced. Ricotti & Ostriker (2004) argued that most Pop III stars should collapse into black holes to avoid producing too much metals with added benefits of additional accretion produced energy.

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